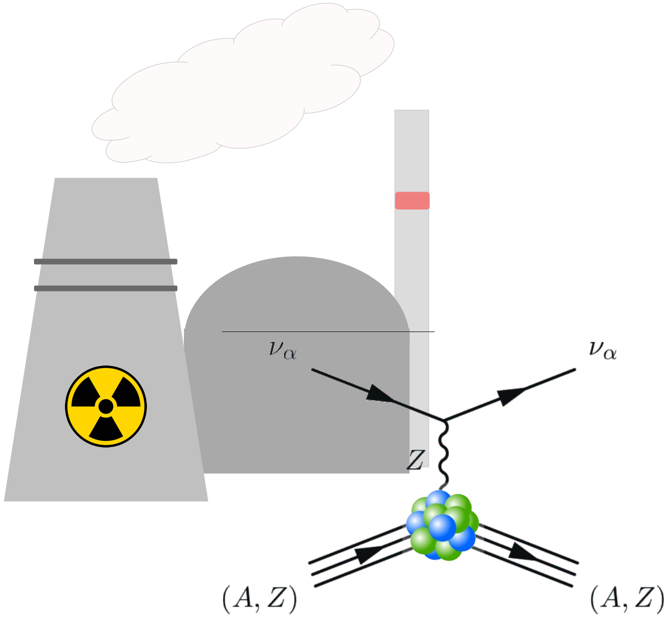


Overview on coherent elastic neutrino nucleus scattering at reactor site

Janina Hakenmüller

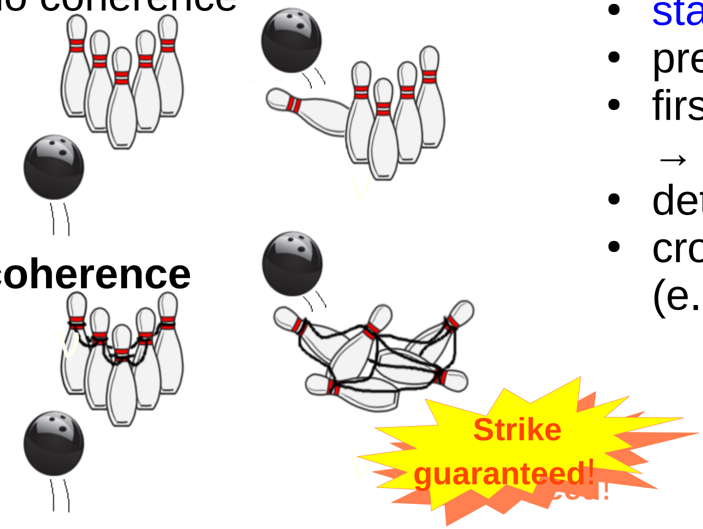
Duke UNIVERSITY

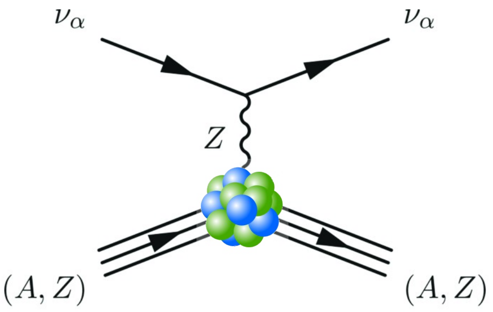
AAP conference, Aachen, 28th of October

Coherent elastic neutrino nucleus scattering (CEvNS)

no coherence

coherence





- standard model interaction, flavor blind, no energy threshold
- predicted in 1974: D.Z. Freedmann, Phys. Rev. 9 (1974) 5
- first detected in 2017: COHERENT experiment
  → CsI detector at pion decay-at-rest source
- detection at nuclear reactor (lower ν energies) still pending
- cross section **large** compared to other neutrino interactions (e.g inverse beta decay)

neutrino energy

$$\frac{d\sigma}{d\Omega} = \frac{G_f^2}{16\pi^2}(N-(1-4\sin^2\theta_W)Z)^2 E_\nu^2(1+\cos\,\theta)F(Q^2)$$

nucleus

nuclear form factor
$F(Q^2) \rightarrow 1$ for $Q^2 \rightarrow 0$

coherence condition:

λ(mom. transfer Q) > size of atom => σ ~ (#scatter targets)^2

→ upper limit on neutrino energy:

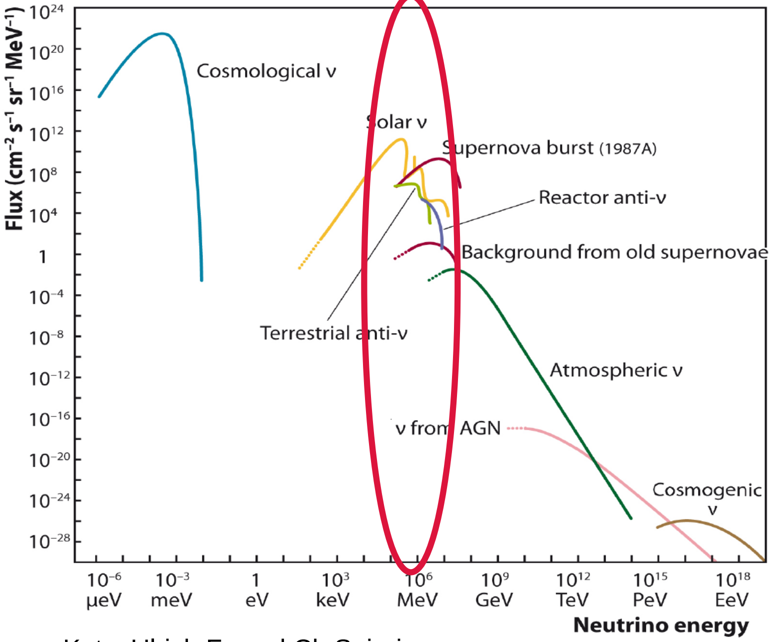
$$E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}} \quad (\mathrm{MeV})$$

E_{max}≤50 MeV (for medium A)

R_A=radius, A= mass number

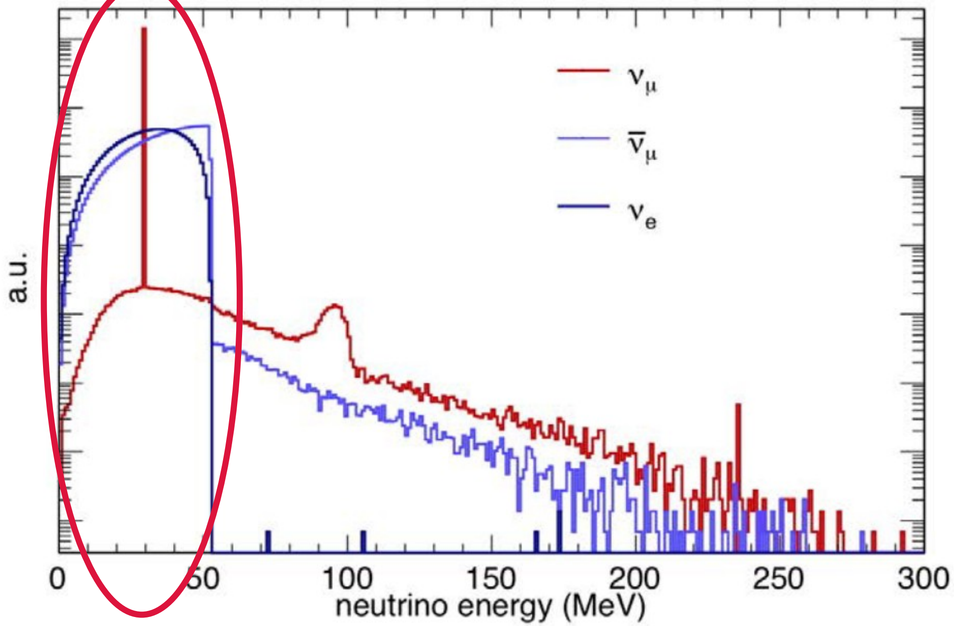
Neutrino sources

natural and reactor neutrinos



Katz, Ulrich F., and Ch Spiering.
Progress in Particle and Nuclear Physics 67.3 (2012): 651-704.

accelerator neutrinos

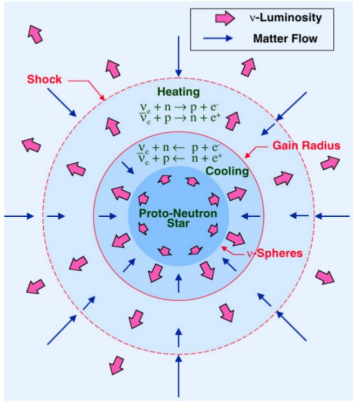


D. Akimov et al., Science 10.1126/science.aao0990, 2017

radioactive decay, solar neutrinos, supernovea, nuclear reactor, spallation source

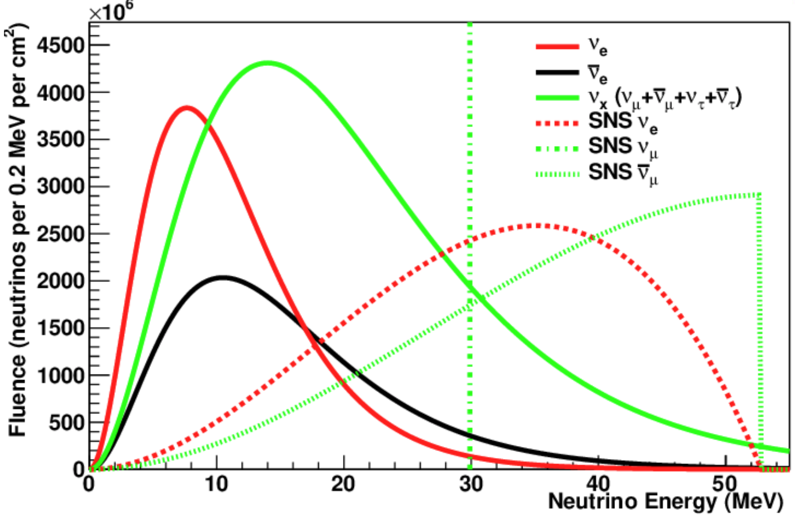
Motivation

- stellar collapse:
  99% energy
  released in neutrinos
  → burst modeling
  → detect on Earth

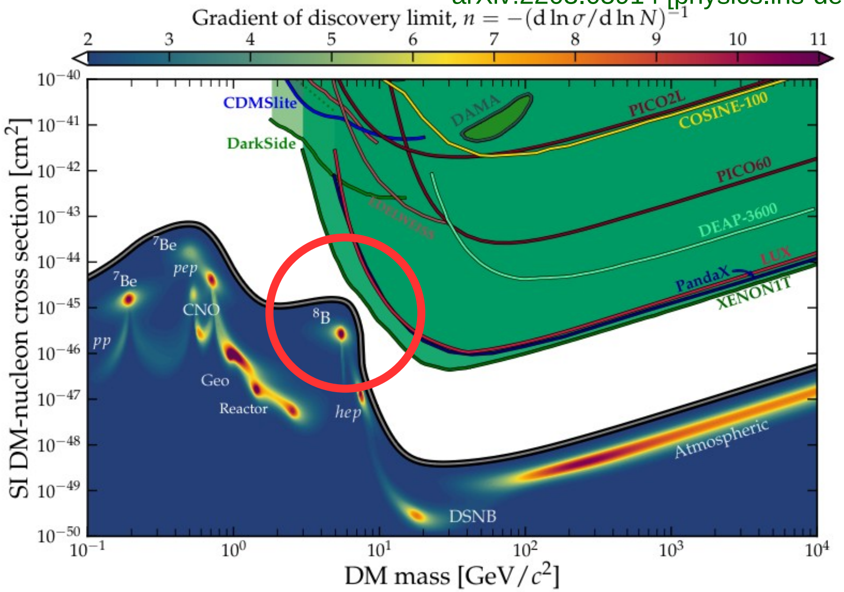


Credit: TeraScale Supernova Initiative

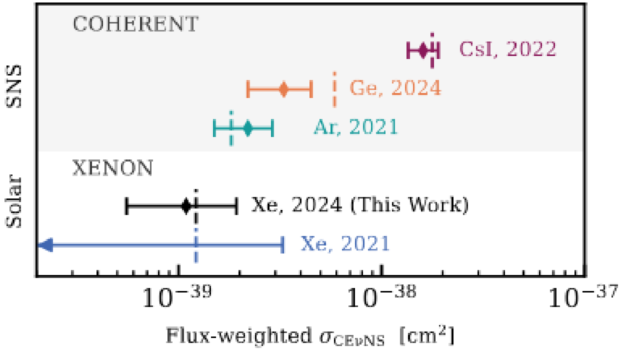
Efremenko, Yu, and William Raphael Hix. JPCS, Vol. 173. No. 1. IOP Publishing, 2009.



arXiv:2203.05914 [physics.ins-det]



- "neutrino floor/fog" in dark matter experiments:
  signature like dark matter → same detector response



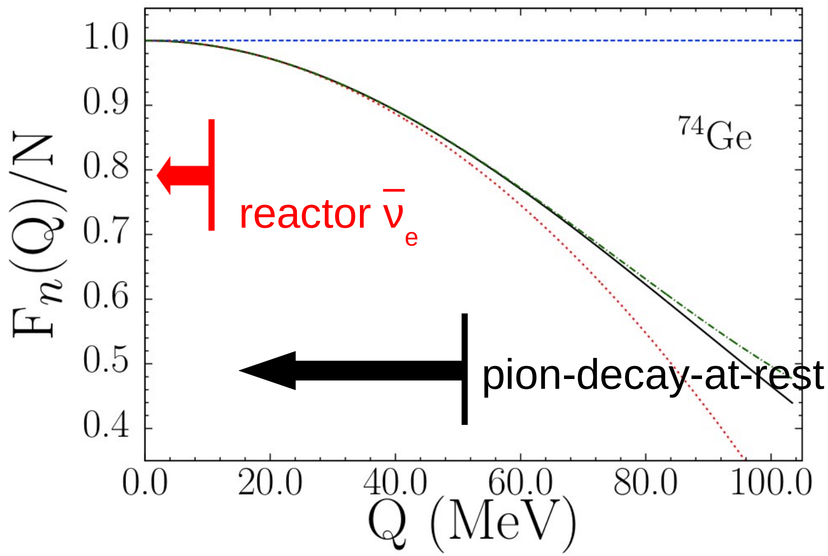
First strong hint this summer!

XenonNT 2.7 σ, arXiv:2408.02877
PandaX 2.6 σ, arXiv:2407.10892

Motivation

Akimov, D., et al. "Physical Review Letters 129.8 (2022): 081801.

neutron form factor F(Q^2)

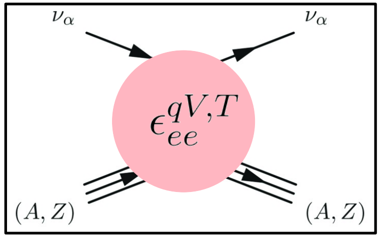


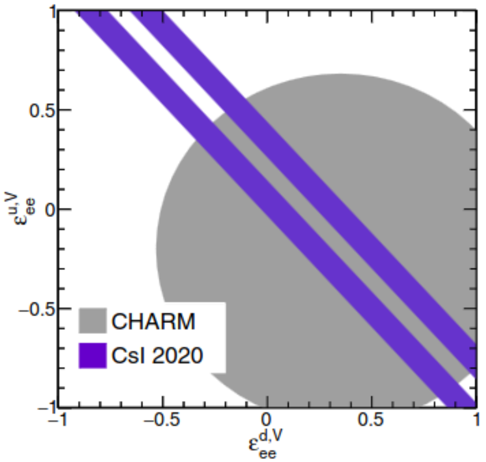
K. Patton et al., Phys. Rev. C 86 (2012) 0246

Weinberg angle at low energies

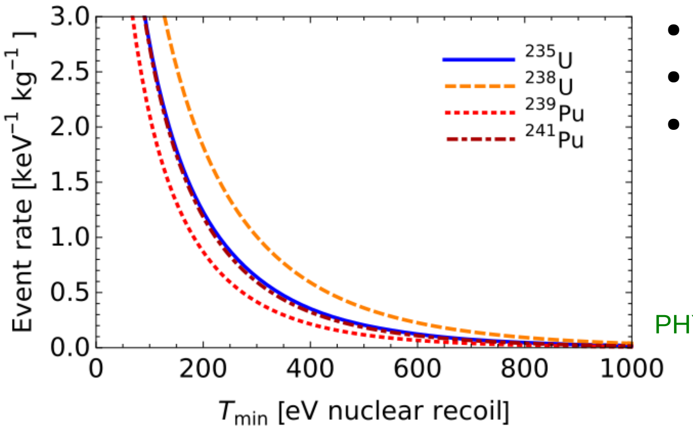
$$\frac{d\sigma}{d\Omega} \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

Beyond the standard model:
non-standard interactions,
light mediators,...





Reactor monitoring and non-profilation



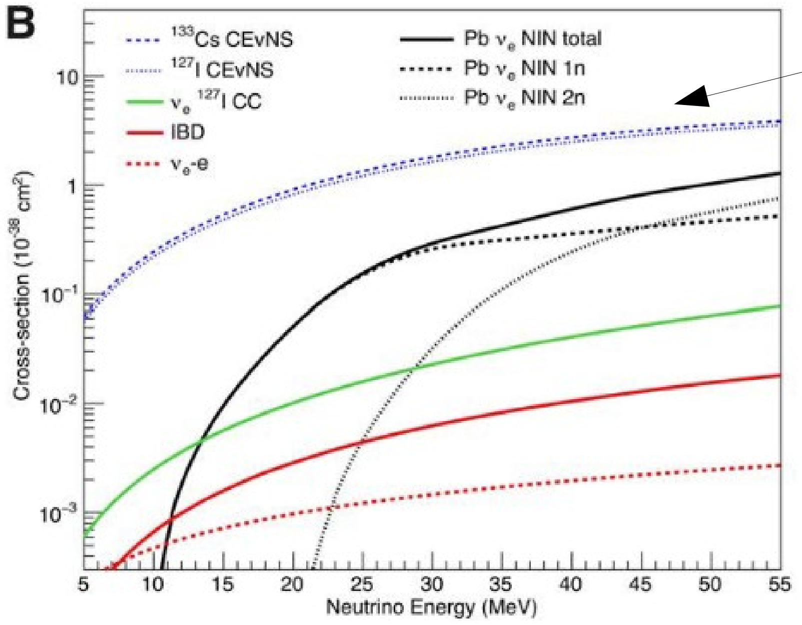
- non-invasive
- spent fuel monitoring
- advanced reactor systems: molten salt-fueled (NuTool report)

PHYS. REV. D 102, 053008 (2020)

Many talks on reactor monitoring with neutrionos
Talk: B. Ryan 29th of Oct., finding trafficked nuclear materials with CEvNS

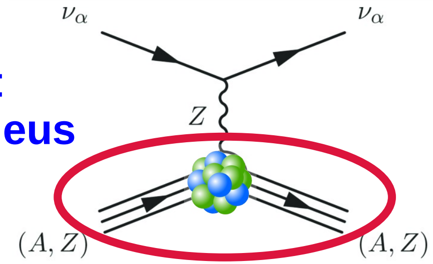
Detecting CEvNS

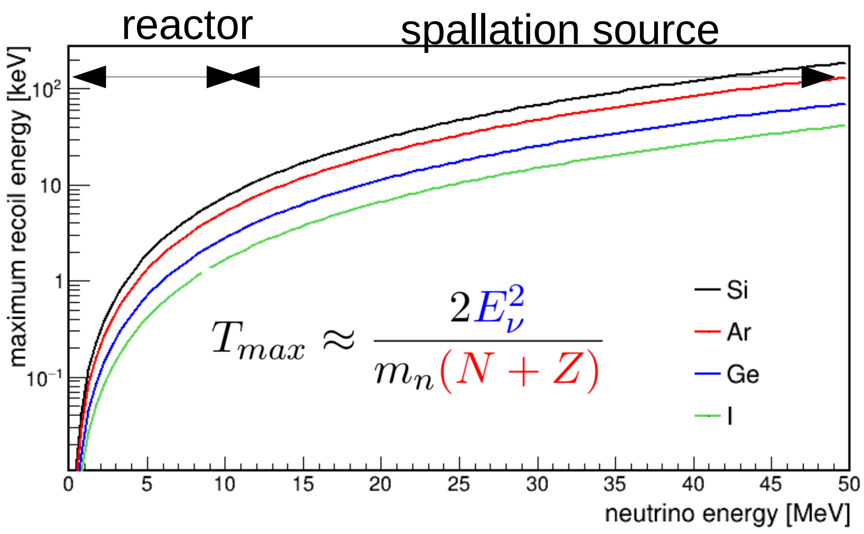
D. Akimov et al., Science 10.1126/science.aao0990, 2017



COHERENT
CsI

Detection parameter:
recoil of target nucleus





$$T_{max} \approx \frac{2E_\nu^2}{m_n(N+Z)}$$

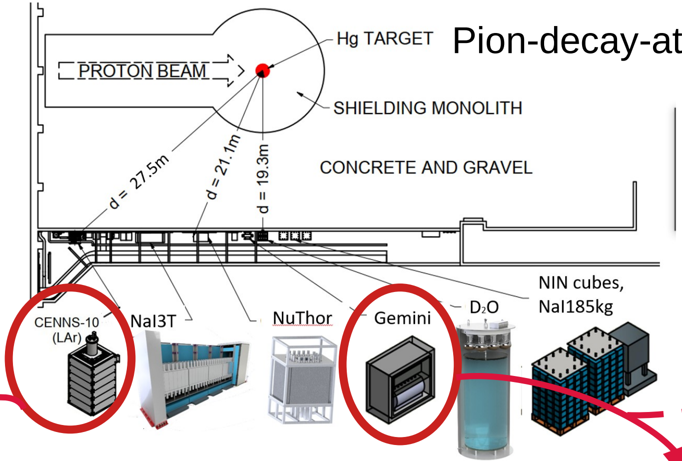
Coherence condition: $\sigma \propto N^2 E_\nu^2$

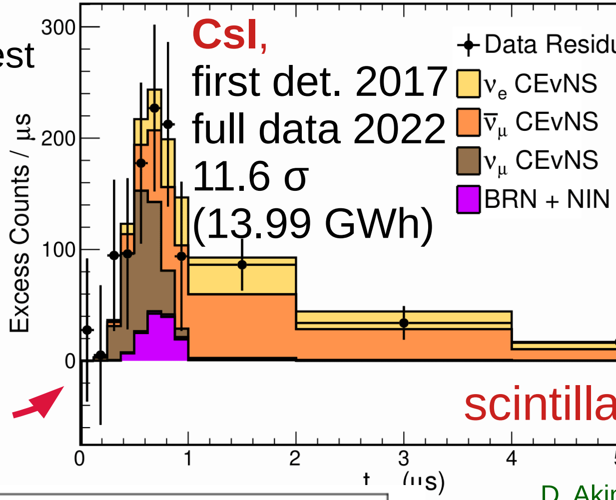
large cross section => small detector (kg sized!)

First detection of CEvNS

Talk: more on COHERENT 30th of Oct.

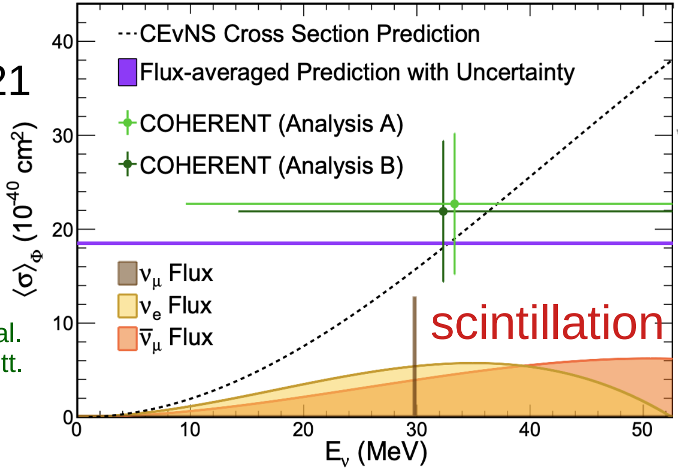
Neutrino alley at spallation neutron source (SNS):
(Oak Ridge, Tenesse, USA)



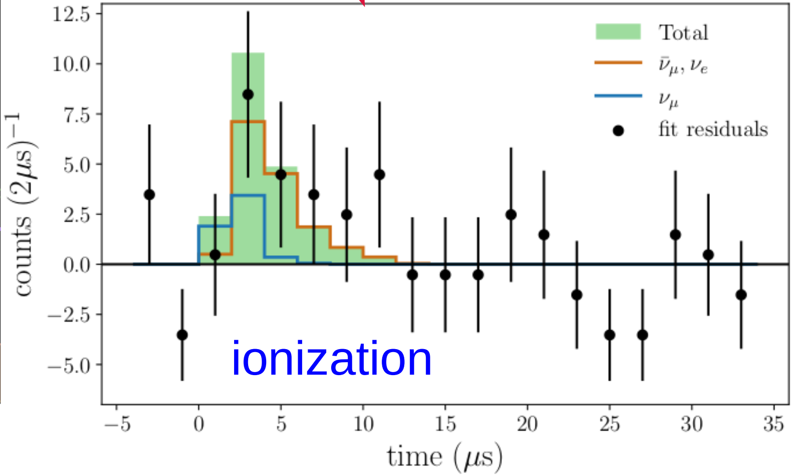


D. Akimov et al. Phys. Rev. Lett. 129, 081801,2022

LAr, 2021
3.5 σ
(6.12 GWh)



D. Akimov et al. Phys. Rev. Lett. 126, 012002, 2021



Ge, 2023, 3.9 σ (4.58 GWh, 6/21/23 - 8/15/23)

Adamski, S., et al., arXiv:2406.13806 (2024).

CEvNS cross section

N^2 dependence ↔ test of standard model physics

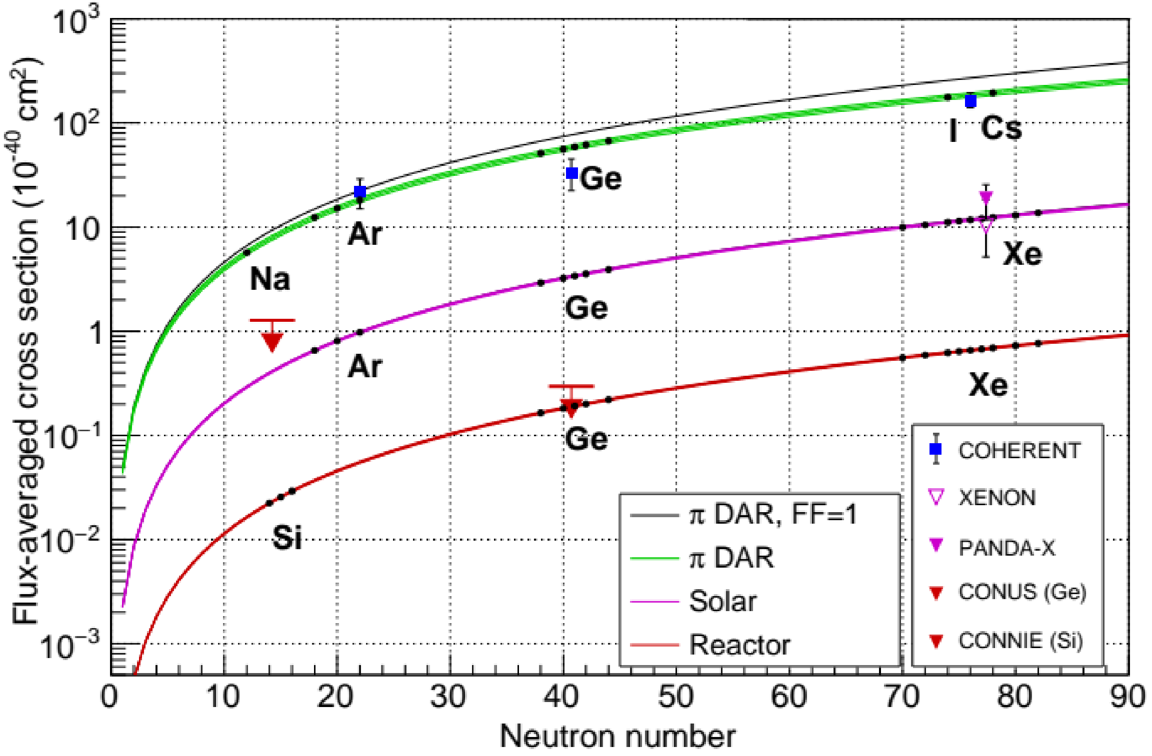


Figure courtesy of K. Scholberg

Comparison πDAR to reactor

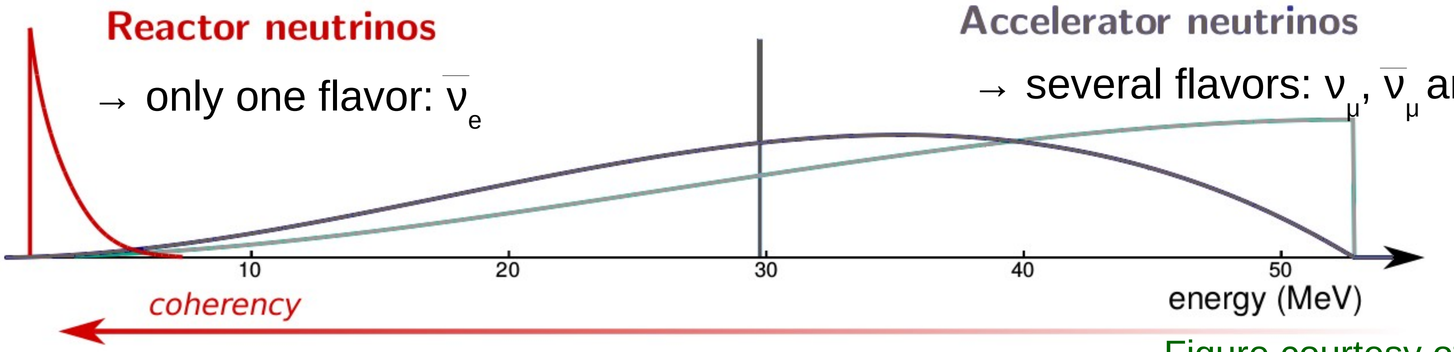
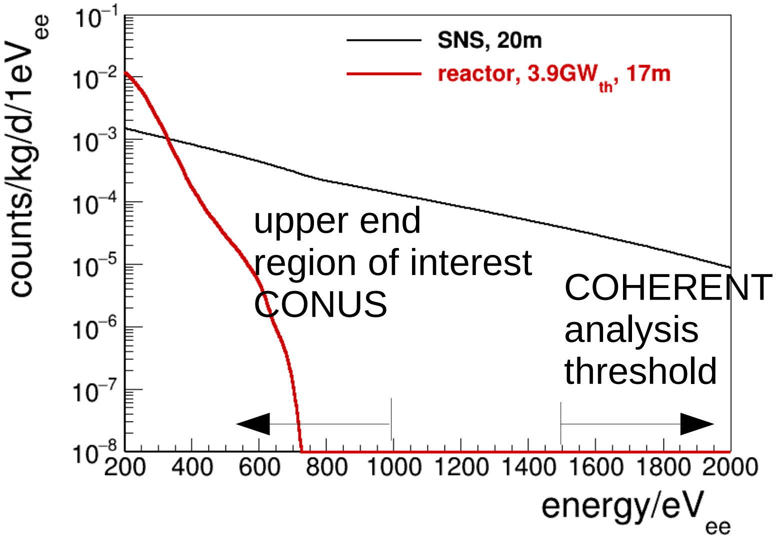
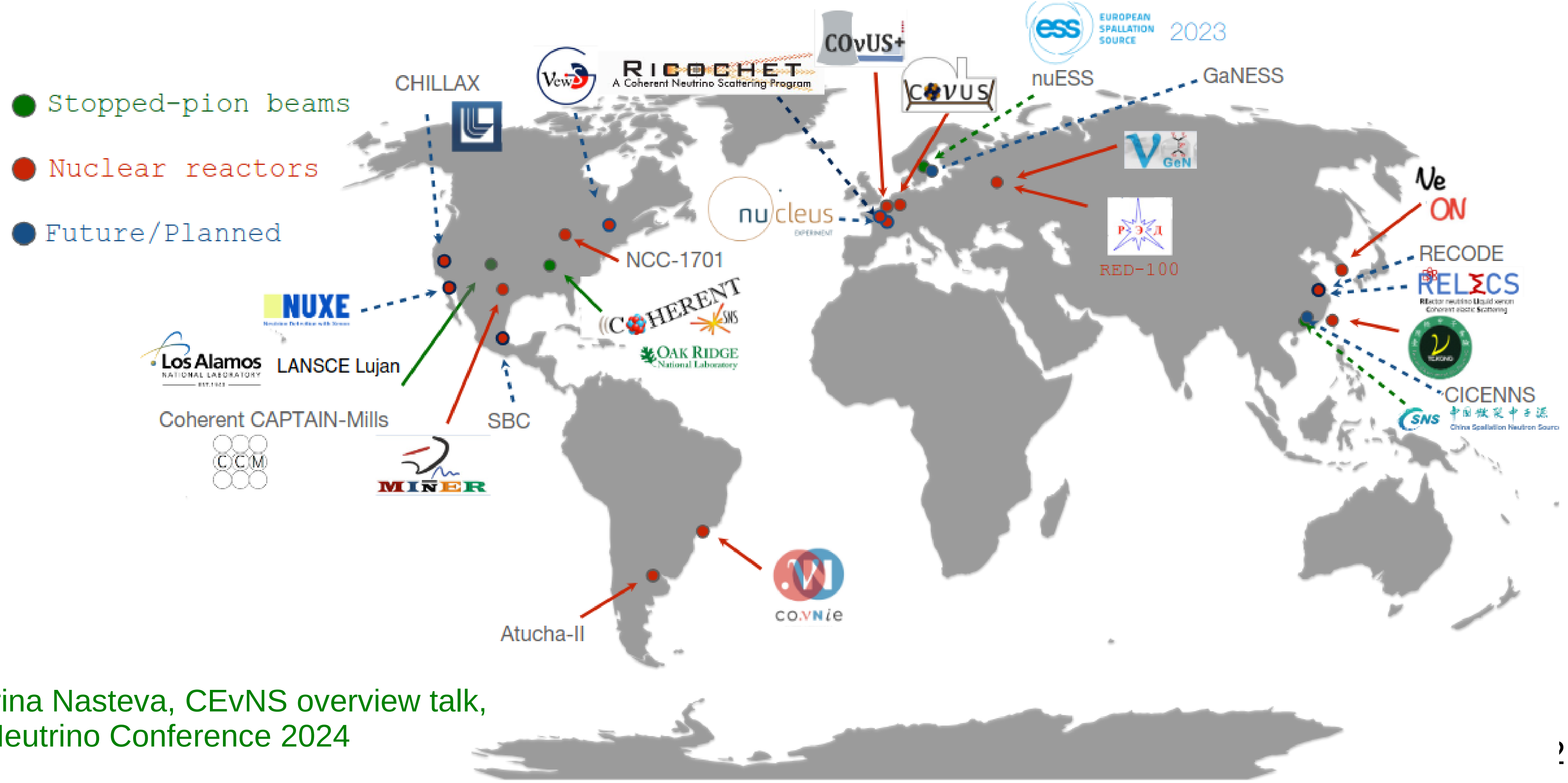


Figure courtesy of A. Bonhomme



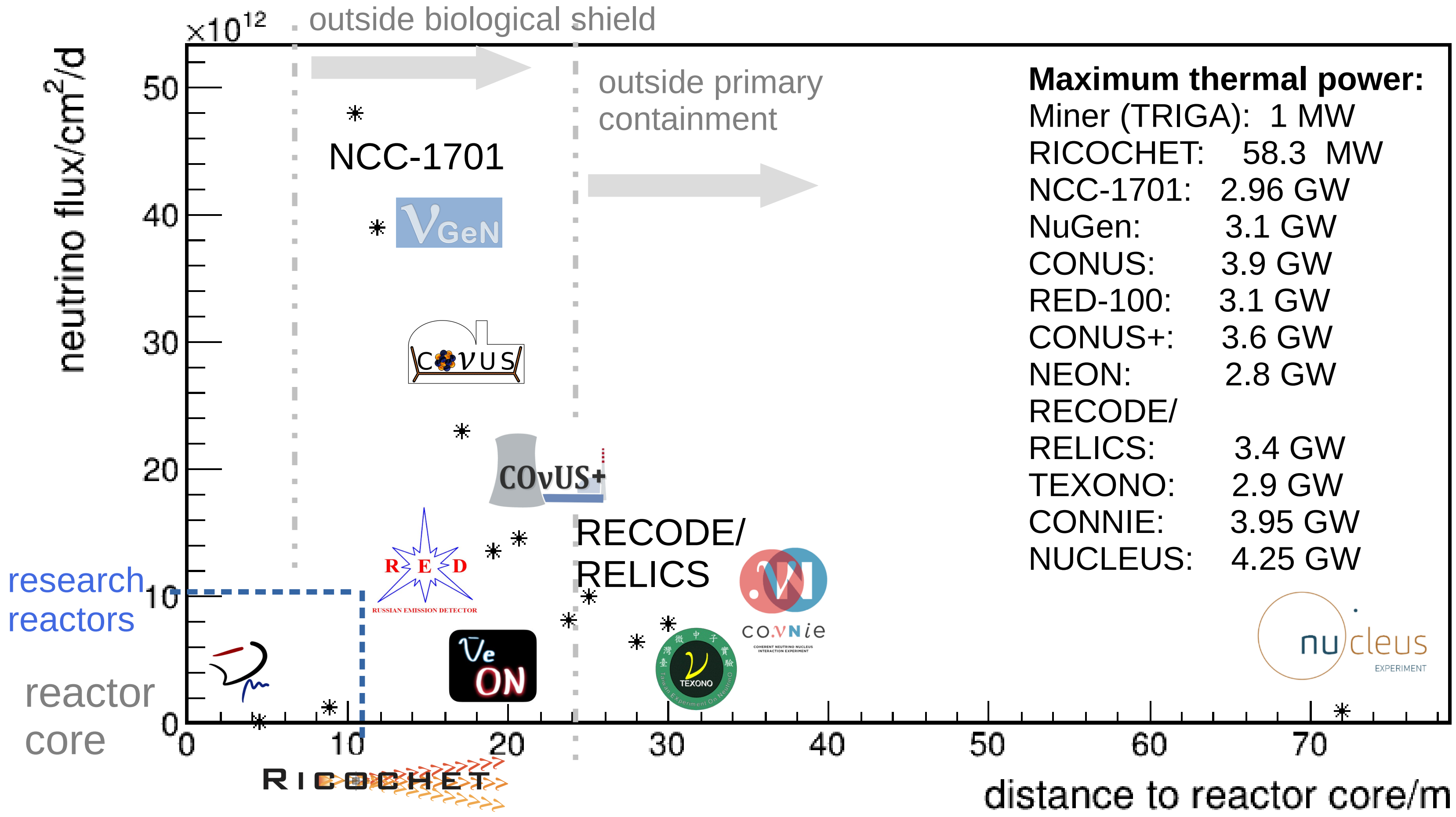
- **Neutrino flux:** total same distance **~10^6 higher at reactor**
- **Neutrino energies** → recoil energies
  => form factor: **~1 at reactor,** <1 at spallation sources
  => threshold requirements e.g. for HPGe:
  << 0.5 keV$_{ee}$ at reactor, < ~10 keV$_{ee}$ at spallation sources
- **Background:**
  shallow overburden => shield (+ muon veto)
  spallation source: pulsed, additional suppression O(10^4)
  reactor: only sparse outages → **excellent shield needed**

Reactor CEvNS around the world



Irina Nasteva, CEvNS overview talk,
Neutrino Conference 2024

Neutrino flux at reactor site

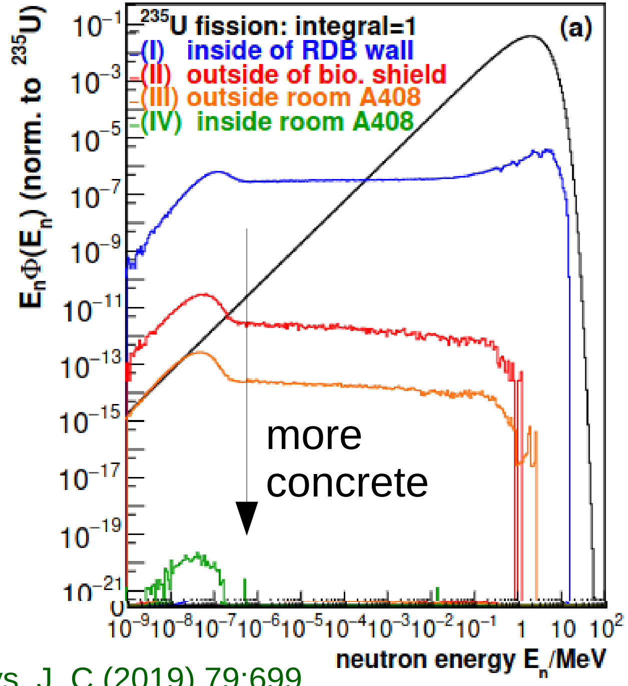


*values reported by experiments

Background mitigation

reactor-correlated

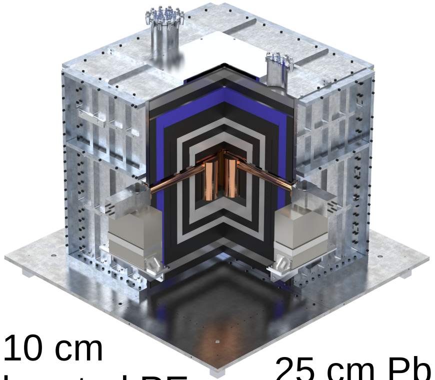
- fission neutrons → recoils like CEvNS
- high-energetic gamma-rays from reactor, cooling cycle or neutron capture



Eur. Phys. J. C (2019) 79:699

=> <u>close to reactor core</u> site characterization necessary!
=> adapt shield design

Example: CONUS shield



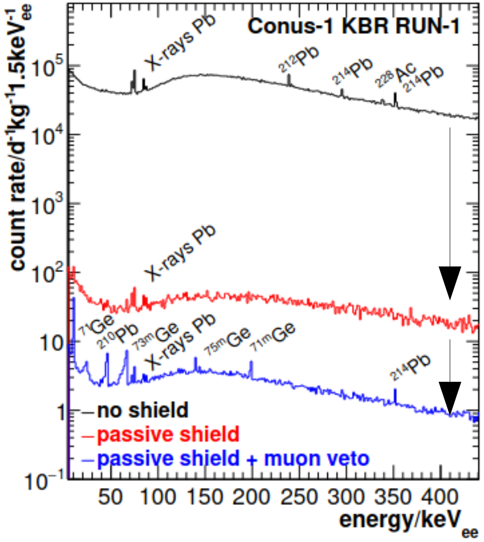
10 cm borated PE

25 cm Pb

muon-induced

mostly no overburden at reactor site
+ high-density materials in shield
=> muon-induced neutrons

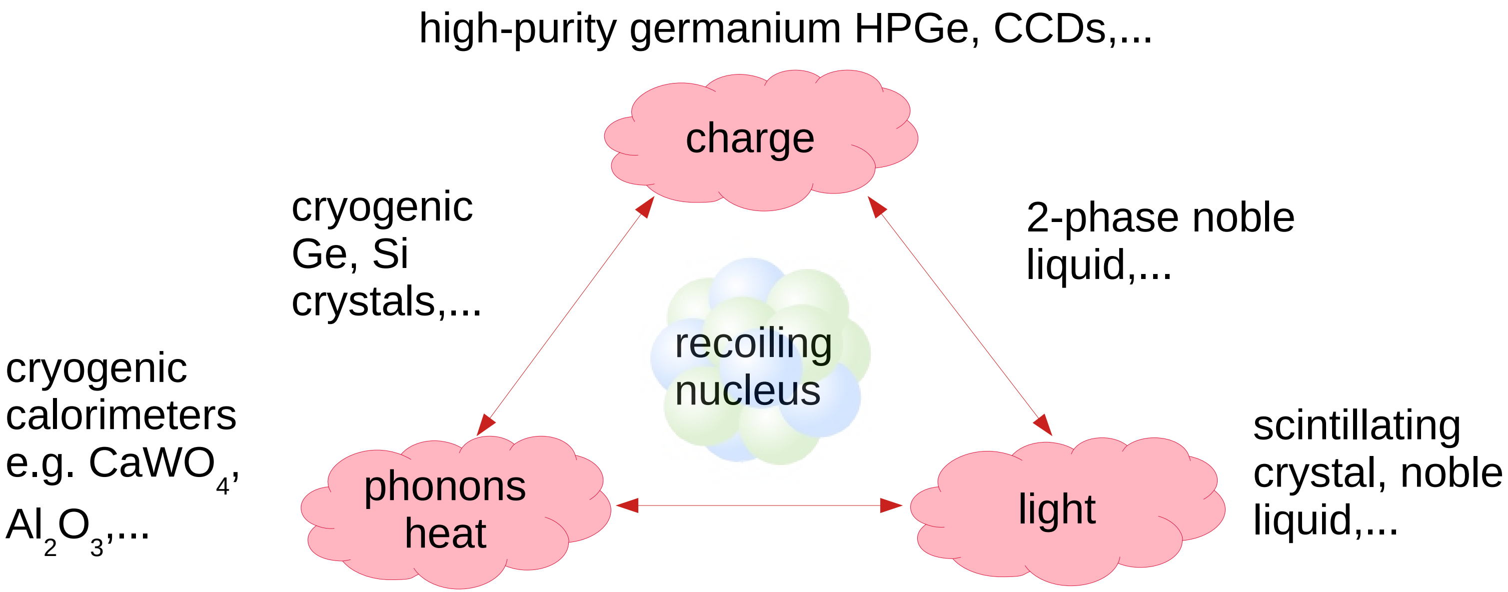
- active veto systems: plastic scintillator, water tank, Ge(NUCLEUS)
- track identification (CCDs)



passive shield

muon veto

CEvNS detectors

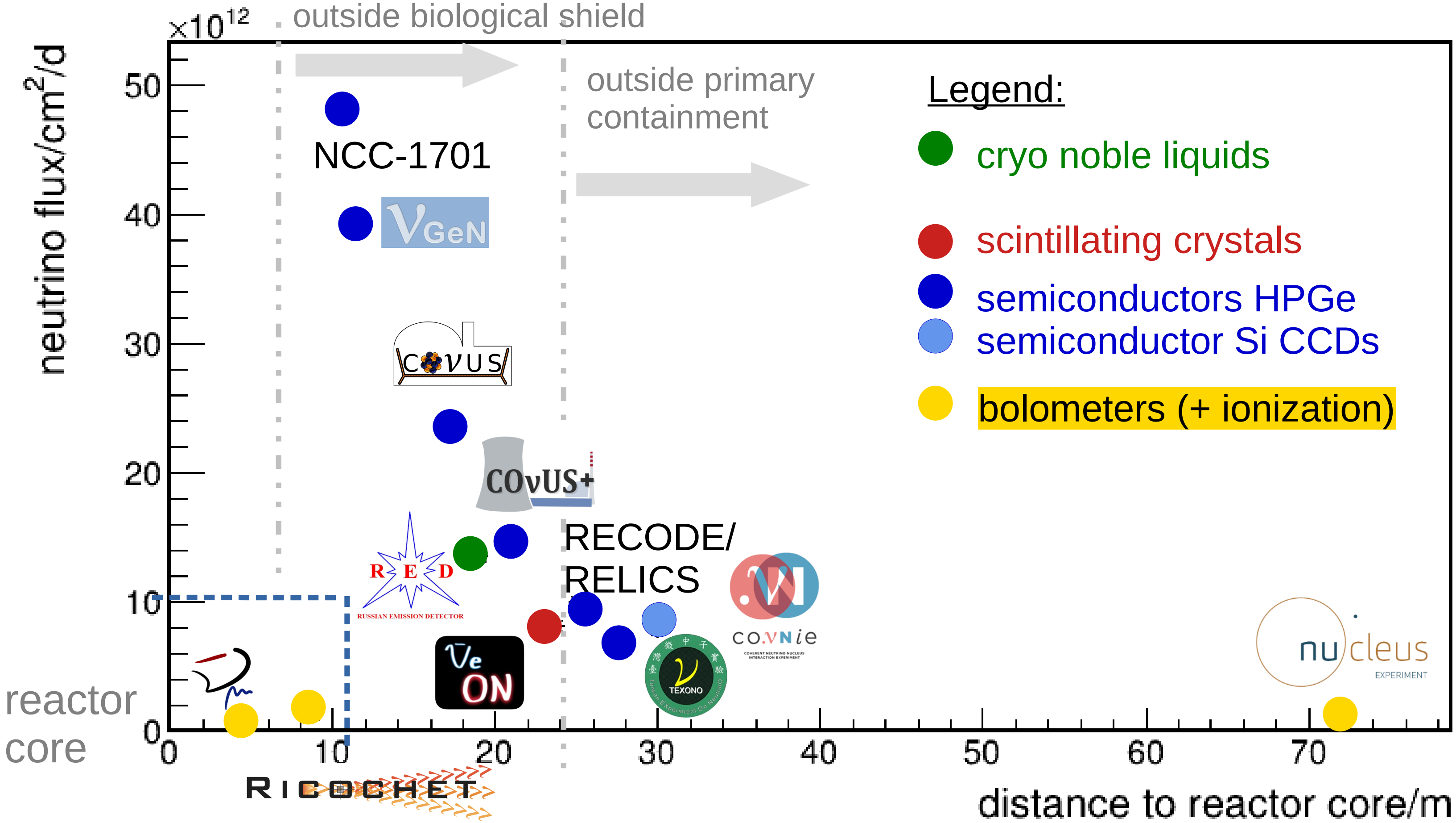


Quenching:

- Quenching factor: $Q=E(meas)/E_{nuclear\ recoil}$
  e.g. HPGe: 1keV recoil → ~20% ionization (read-out), ~80% phonons (not read-out)

=> often not (yet) well known at low recoil energies for CEνNS
=> major uncertainty for some technologies, quenching measurements!

Neutrino flux at reactor site



mass

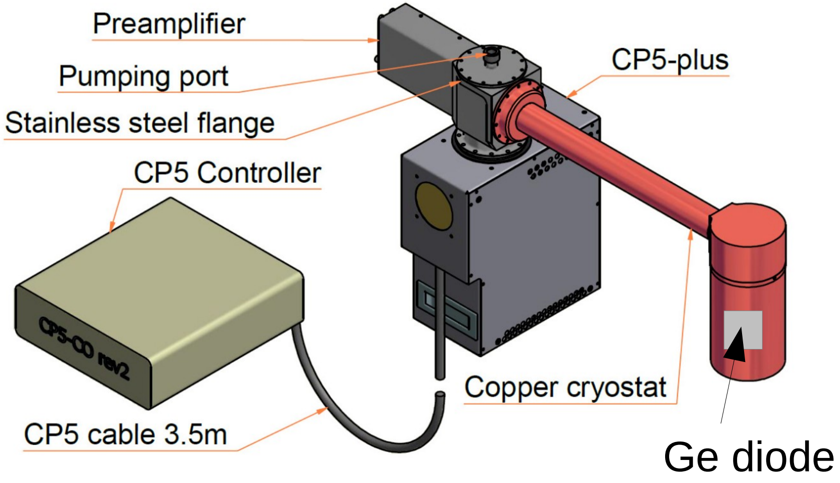
nuclear recoil thr.

different isotopes
→ test N^2 dep. of cross section

*values reported by experiments

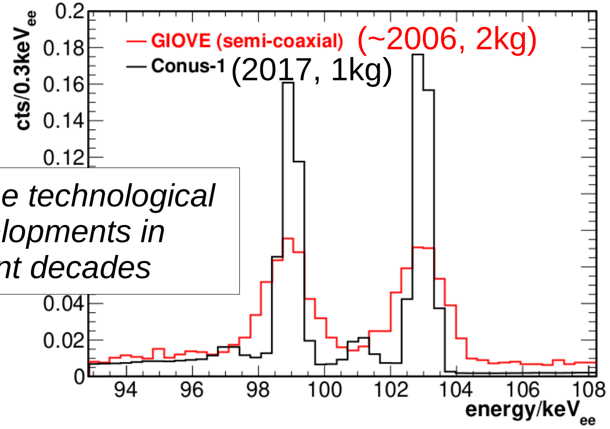
High-purity Ge spectrometer

ionization energy
mass: O(1 kg)
rec. thr.: O(1 keV_{nr})
quenching: yes



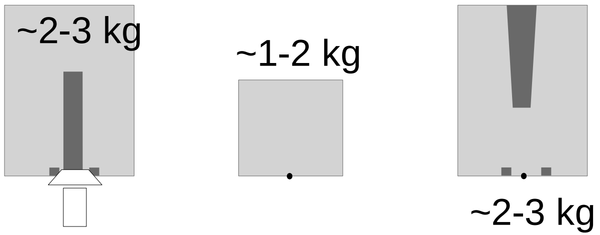
	mass/kg	threshold/eVee (trigger efficiency)
NCC-1701	2.4	200 (>0%)
NuGen	1.4	290 (~85%)
CONUS CONUS+	4 4	210 (>20%) ~160 (100%)
TEXONO RECODE	2 tbd	200 (~100%) aim 160 (tbd)

PRD 104, 072003 (2021)
https://indico.cern.ch/event/1342813/contributions/5913887/
arXiv:2401.07684v2
arXiv:2407.11912 (2024)
PoS (TAUP2023) 226
https://indico.cern.ch/event/1342813/contributions/5913896/

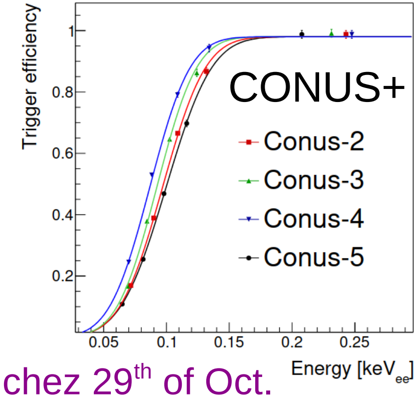


HPGe technological developments in recent decades

detector design evolution



→ smaller contact, larger mass

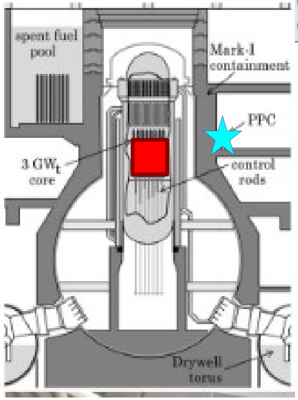


smaller point contact, water cooling

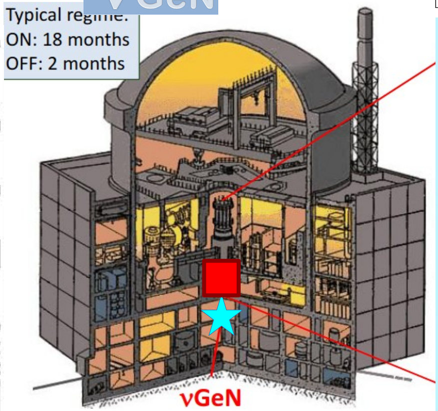
Talk: E. Sanchez 29th of Oct.

HPGe at reactor site

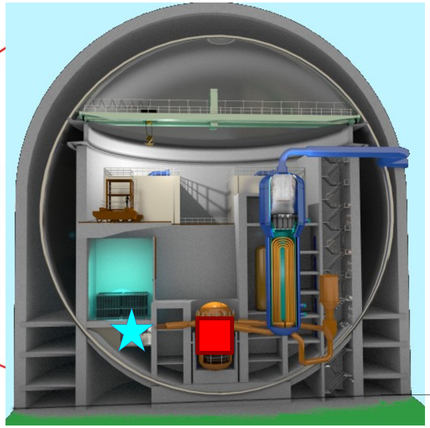
NCC-1701, USA
→ Sweden?



Russia

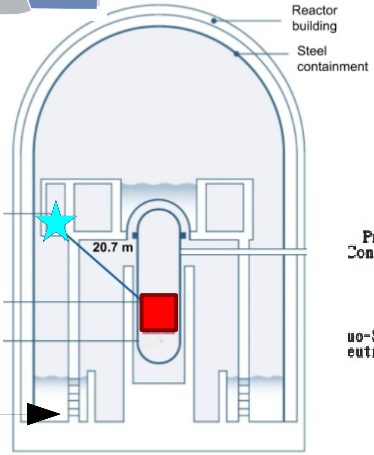


Germany

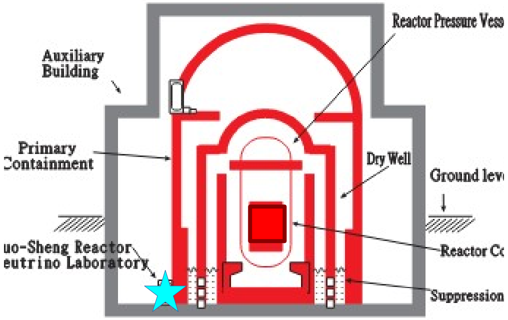


reactor shut down

Switzerland

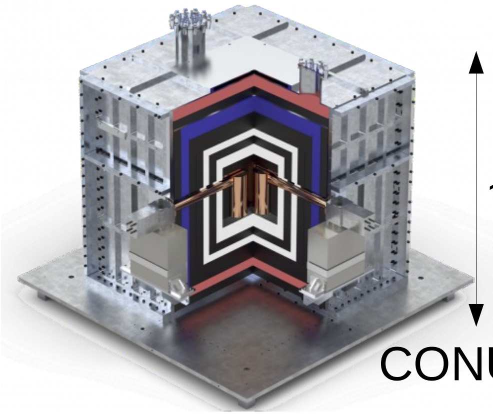


Taiwan
→ RECODE, China



reactor shut down

Muon veto



~1 m

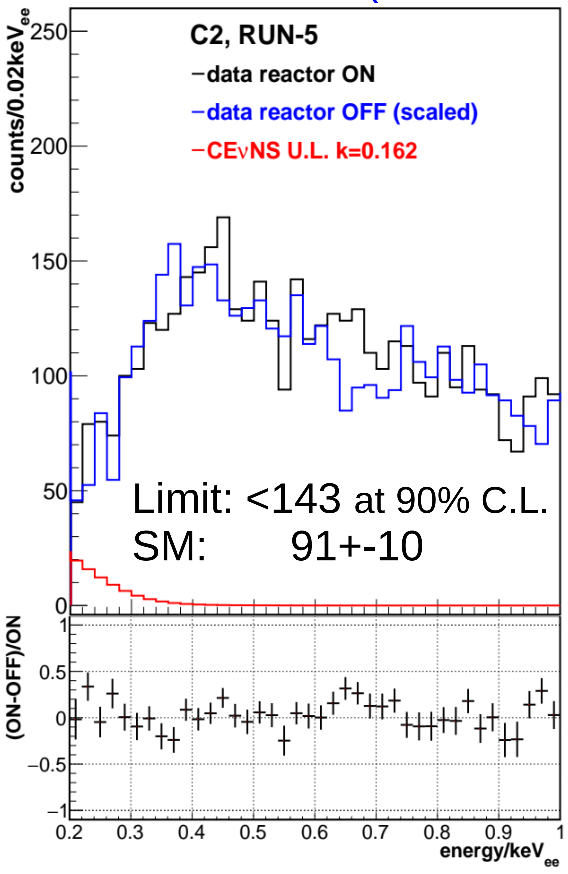
CONUS shield

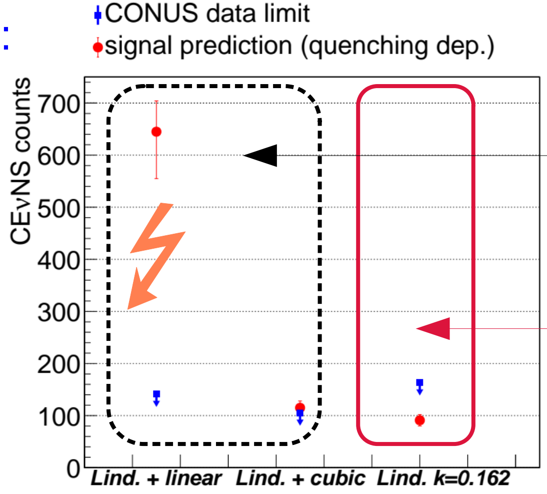
	bkg level ROI cts/d/kg/keV
NCC-1701	~2000, ~500
NuGen	~30
CONUS	~20
TEXONO	~50

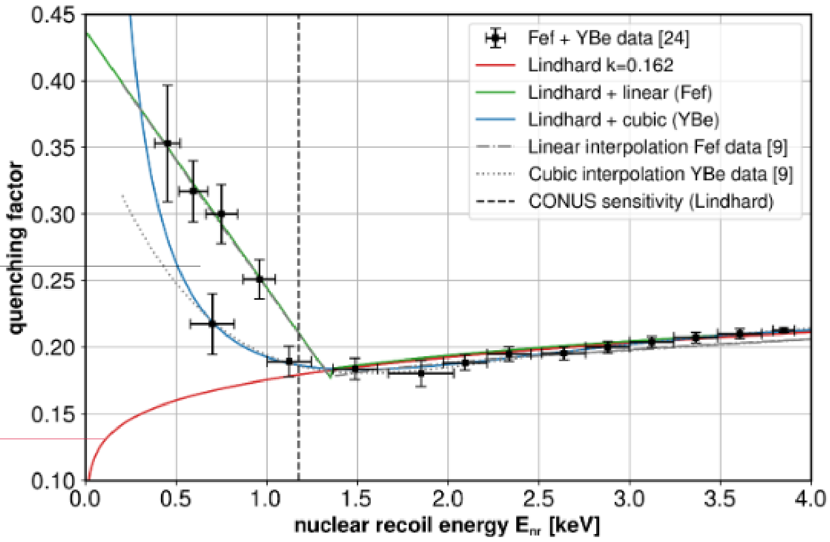
ON to OFF difference

HPGe results

CONUS Run-5 (2021-2022):







	Limit Lindhard theory	**exposure kgd of ON/OFF**
CONUS	x2 SM (k=0.162)	426/272
TEXONO	x4 SM (k=0.157)	65/438
NuGen	x5 SM (k=0.162)	192/53
NCC-1701	SM CEvNS only for alternative Qf	231/60

Talk: K. Ni 29th of Oct.

arXiv:2401.07684v2

PoS (TAUP2023) 226

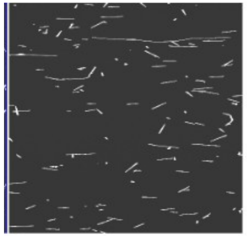
https://indico.cern.ch/event/1342813/contributions/5913887/

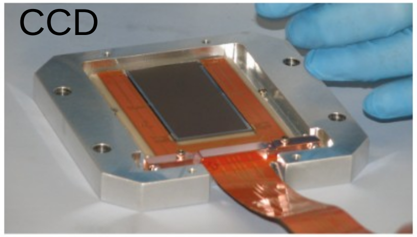
Phys. Rev. Lett. 129 (2022), 211802

Si Charge coupled devices CCDs

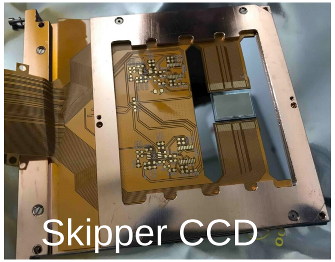
ionization energy
mass: O(1-10 g)
rec. thr.: O(0.01 keV_{nr})
quenching: yes

- imaging detector with pixelated readout, very low noise
- cooled to ~130-140 K, low mass, slow readout O(10 min)
- quenching: Sarkis model agrees with data (Lindhard theory + binding energy effects)
- detector upgrade: Skipper CCDs conserve charge during readout, sample charge in each pixel multiple times } significantly lower threshold



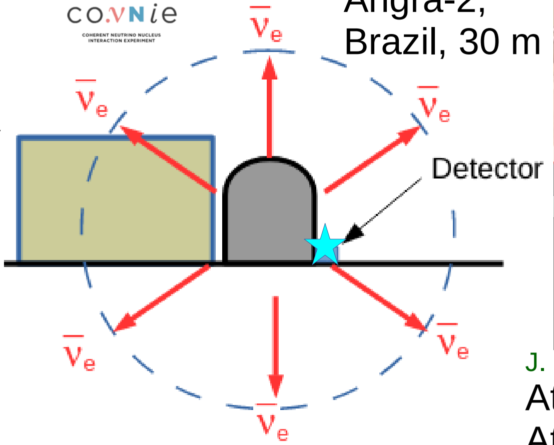


JINST 11 (2016) 07, P07024

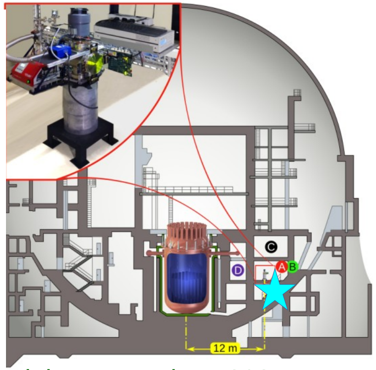


arXiv:2403.15976

Angra-2, Brazil, 30 m



2016 J. Phys.: Conf. Ser. 761 012057



J. High Energ. Phys. 2024, 155

Atucha-II experiment,
Atucha-II, Brazil, 12 m

+ Violeta

	ion. thr. eV_{ee}	**mass**	**Exposure** ON/OFF	**Limit**
CONUS (HPGe)	210	4 kg	426 kgd, 272 kgd	SM x2
CCDs (CONNIE)	50	8 x 6 g	1.2 kgd, 1.0 kgd	SM x66
Skipper CCDs (CONNIE)	15	2 x 0.25 g	14.9 gd, 3.5 gd	SM x76

planned upgrade:
more exposure needed
→ more skipper CCDs, 8g in 2024

JHEP 05 (2022) 017
arXiv:2403.15976

Cryo noble liquids

- two-phase gas emission detectors
- Target fiducial volume:
  - RED-100 100 kg liquid Xe
  - RELICS: 32 kg liquid Xe (planned)
- RED-100: Akimov D. Y., et al. JINST 17.11 (2022), T11011

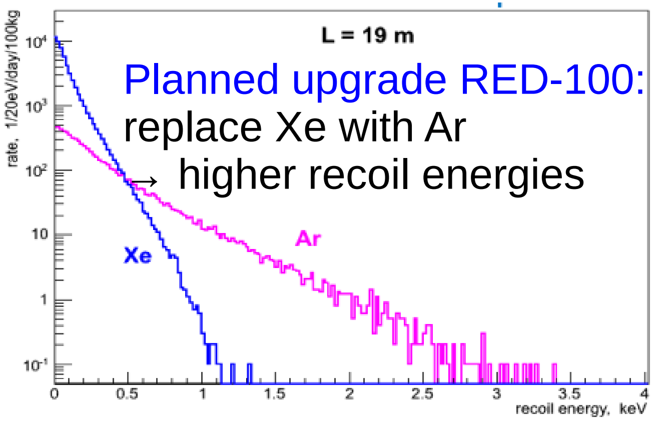
  threshold: 4. photoelectrons ↔ ~0.5 keV_{nr}

  Below: huge single electron noise bkg

  → reduction in analysis, ML

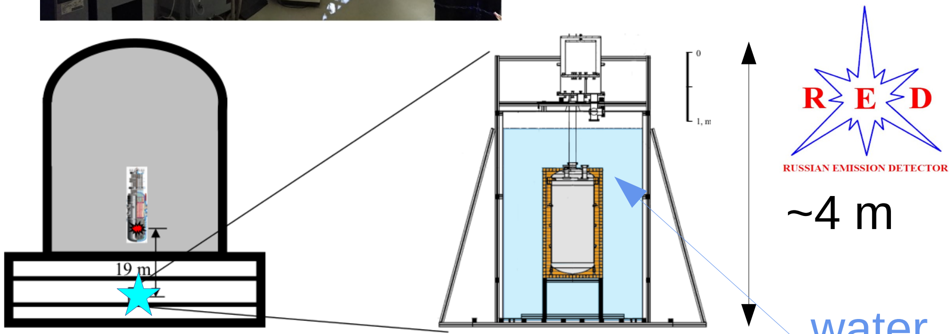
  first result: **63-94x SM** (prelim.)

https://indico.particle.mephi.ru/event/436/contributions/4291/attachments/2490/4615/ICPPA2024_RED100.pdf



Planned upgrade RED-100:
replace Xe with Ar
→ higher recoil energies

light/charge
mass: O(10-100 kg)
rec. thr.: O(1 keV_{nr})
quenching: yes



~4 m

water tank

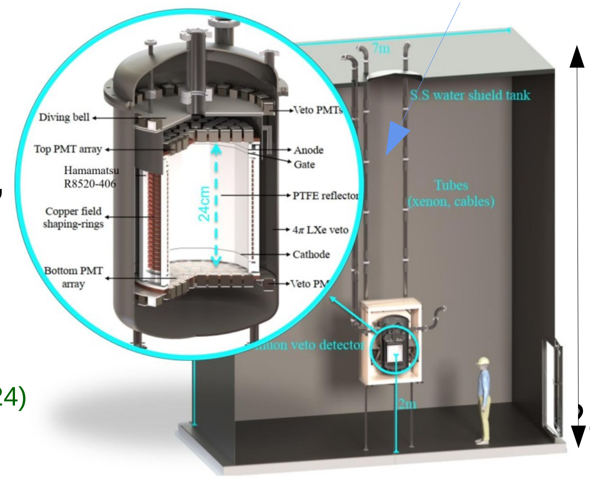
KNPP, Russia, 19 m
https://indico.cern.ch/event/1215362/contributions/5300022/

RELICS
REactor neutrino LIquid xenon Coherent elastic Scattering

Sanmen reactor, China, planned outside the containment at 25 m distance
→ no overburden

PHYS. REV. D 110, 072011 (2024)

+ NUXE



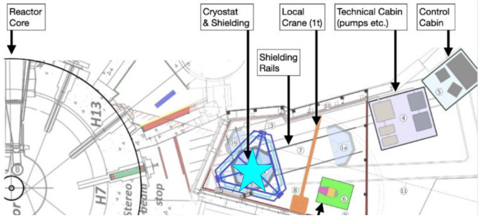
~7 m

Bolometers/cryogenic calorimeters

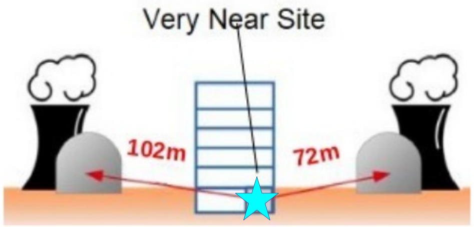
heat,
heat + ionization
mass: O(1-100 g)
rec. thr.: O(10-100 eV_{nr})
quenching: no

- recoil-incuded temperature change
- cryogenic temperatures in mK range → large setups → practical constraints
- vibration migration important
- RICOCHET: CryoCube (Ge, ionization + heat), Q-Array (Zn, heat) ~> O(100 eV_{nr})
- NUCLEUS: crystal Al_2O_3, $CaWO_4$ + transition edge sensor (TES) ~> O(10 eV_{nr})

aim



research reactor 58 MW
ILL, France, 8.8 m

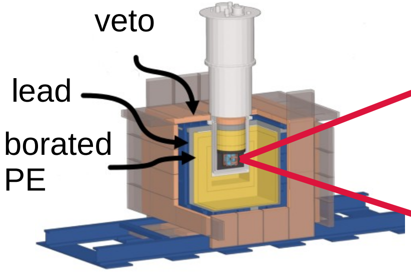


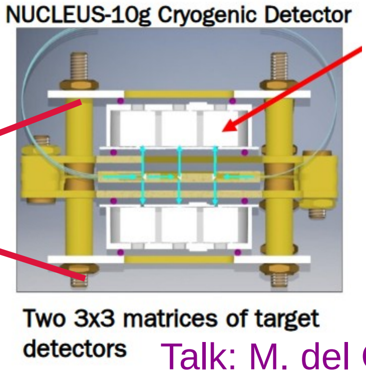
Chooz reactor, France, 72/102 m

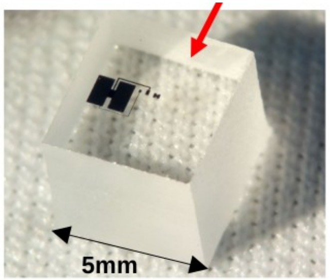
nucleus EXPERIMENT

commissioning at TUM,
2025 deployment at Chooz

progress in low energy excess in heat channel!







https://indico.cern.ch/event/1215362/contributions/5299993/

Talk: M. del Gallo 30th of Oct.

RICOCHET

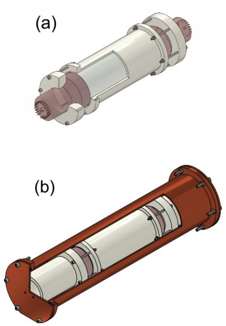
2023: 30eV_{ee} resolution shown for CryoCube
2024: commissioning at ILL
2025: start of data taking planned

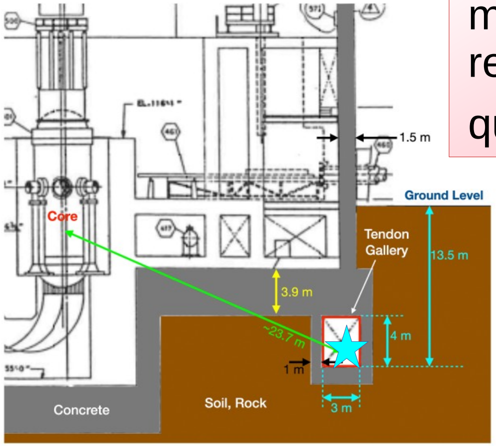
Talk: N. Dombrowski 29th of Oct.

+ MINER

Scintillating crystals and R&D

Hanbit, Korea, 24 m





light
mass: O(1 kg)
rec. thr.: O(1 keV_{nr})
quenching: yes

increased light yield from adapted encapsulation: up to 22 NPE/keV
excellent background level
aimed threshold: 5 NPE → ~0.2 keV_{ee}

reactor data since May 2021
total mass 6 crystals: 12.5 kg

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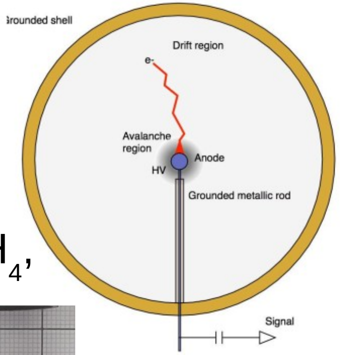
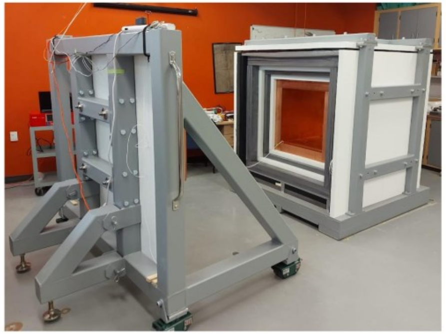
Spherical proportional counters
(ionization energy)

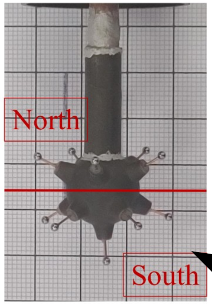
Pressurized gas:
Ne + 3% CH_4,
...





NEWS-G3: same technology as dark matter experiment NEWS-G
aimed energy threshold: 50 eV_{ee}

no reactor site (yet)
potential for directionality!



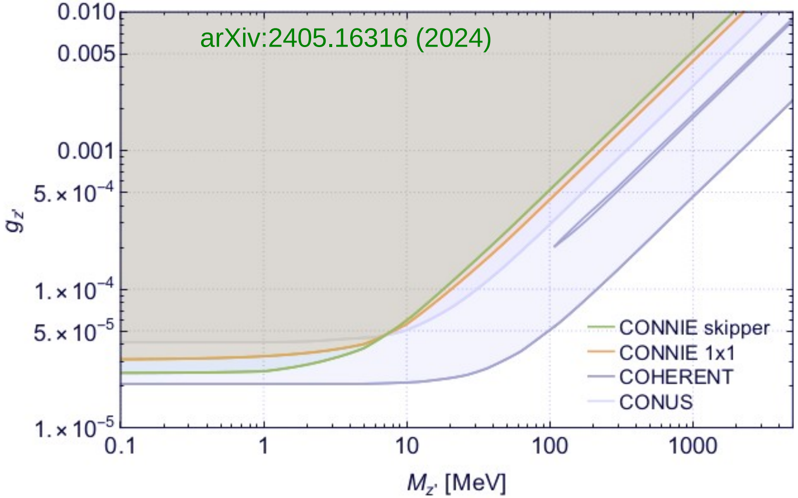
PALEOCCENE: recoil traces in materials, passive color center detectors, potential for directionality

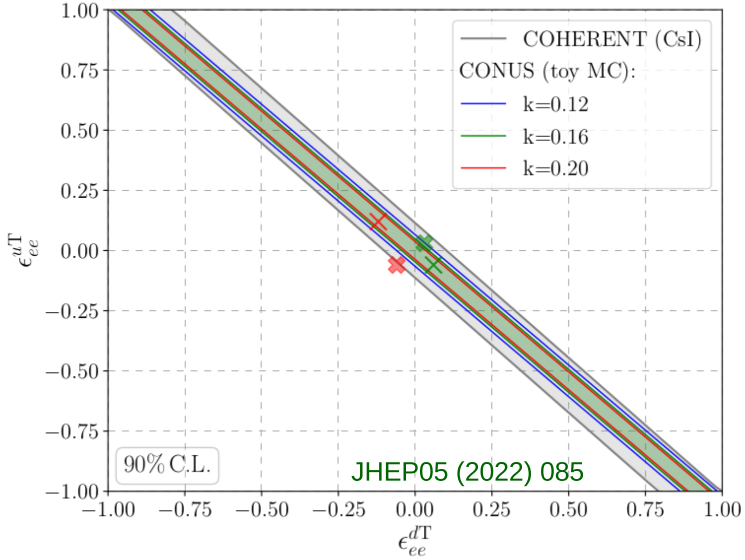
Talk: G. Rodrigues-Araujo 29th of Oct.

+ lots of R&D: SBC, gaseous Xe TPCs,...

Beyond the standard model

→ deviations in rate and/or shape from the SM expectation





non-standard neutrino interactions (NSI),...

light mediators: vector, scaler

neutrino magnetic moment:

CONUS (2022): $\mu_\nu < 5.2 \cdot 10^{-11} \mu_B$

(PhD thesis, J. Hempfling, Heidelberg 2024)

TEXONO (2006): $\mu_\nu < 7.4 \cdot 10^{-11} \mu_B$

Phys.Rev.D75:012001

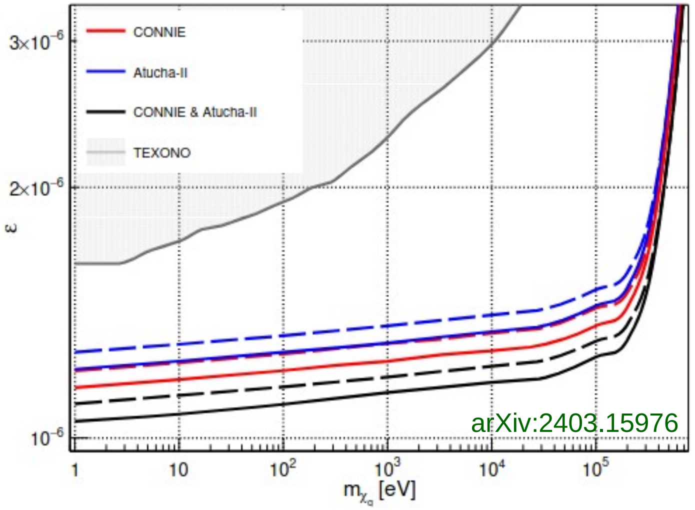
GEMMA: $\mu_\nu < 2.9 \cdot 10^{-11} \mu_B$

Phys. Part. Nuclei Lett. 10, 139–143 (2013)

~one order of magnitude above tonscale experiments

neutrino milli charge:

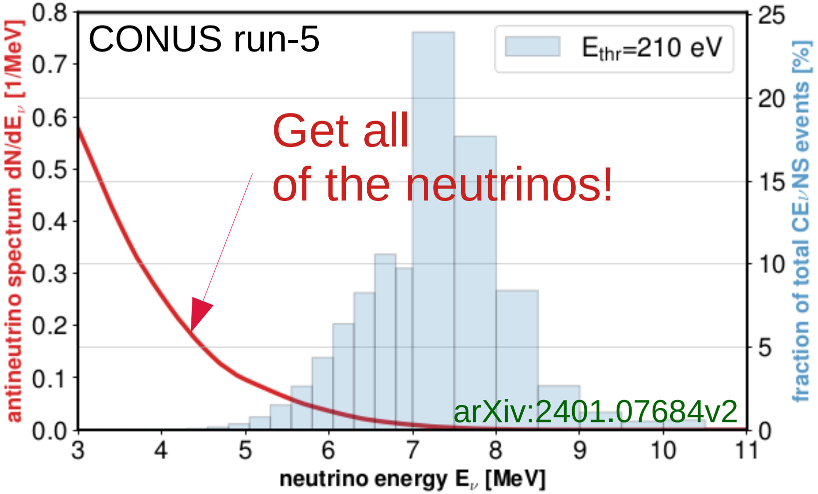
$$q_\nu^2 < \frac{T}{2m_e}\left(\frac{\mu_\nu}{\mu_B}\right)^2 e_0$$



millicharged particles

Summary

CEvNS=interaction of the neutrino with the nucleus as a whole
signature= tiny recoil of the neutrino hit by the nucleus → quenching
first observation 2017 at SNS by COHERENT, two more detections
→ precision test of SM, neutrino fog, supernovae, nuclear form factor, Weinberg anlge, NSI, light mediators, reactor monitoring,….



Multitude of efforts to detect reactor CEvNS!
relationship: mass ↔ threshold
HPGe (4 efforst): CONUS <2x SM
→ upgrades: lower threshold, new reactors
CCDs (3 efforts): CONNIE <66x SM
→ upgrades: more exposure for skipper CCDs
two phase liquid Xe (2 efforts): RED-100 <63-94x SM
→ upgrade: Xe to LAr (single PE background)
heat detection/bolometers (2 efforts): commissioning phase
+ scintillating crystals, proportional counter, gaseous TPCs, R&D for directionality,...

Thank you for your attention!